Complementary Assets as Pipes and Prisms: Innovation Incentives and Trajectory Choices

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Abstract

A long-standing interest in the technology strategy domain has been the failure of established enterprises in the face of radical technical change. In explaining incumbent failure, previous research focuses on incumbents’ under-investment in radical innovations. Despite this established perspective, however, it is commonly observed that incumbents make substantial investments in radical innovations at a magnitude no less than entrants. In order to address the paradox of incumbent failure despite heavy investments, we develop an analytical model that considers firm heterogeneity with respect to both technical trajectories and complementary capabilities. In this model, complementary assets play a dual role in incumbents’ investment behavior toward radical innovations: complementary assets are not only resources [pipes] that can buffer firms from technology change, but are also prisms through which they view those changes, in terms of both the magnitude of resources that should be invested and the trajectory to which these resources should be directed. When complementary assets are specific to a less promising technical trajectory, the incumbent is faced with a tradeoff between leveraging complementary assets and choosing a more promising technical trajectory. This analytical structure is used to provide insight into a number of empirical observations and offer new empirical implications.
1. Introduction

A long-standing interest in the technology strategy domain has been the question of the failure of incumbent firms in the face of radical technical change (Agarwal and Helfat 2009, Christensen 1997, McGahan 2004, Taylor and Helfat 2009, Tushman and Anderson 1986). In explaining such failure, early work within economics, such as Reinganum (1983) and Arrow (1962), stressed the incentives established firms face with respect to innovations that might replace their existing products or services. The strategy literature, such as Tushman and Anderson (1986), and work on evolutionary economics, such as Dosi (1982) and Nelson and Winter (1982), emphasized the distinct capabilities that alternative technology trajectories may require.

Both the economics and the strategy literature predict that incumbent firms fail because they under-invest in radical innovations. An innovation is radical in the economic sense if the new technology is a preferred substitute for the old technology (Arrow 1962, Reinganum 1983); for such innovations, the incumbent’s investment in innovation will cannibalize its existing products. Consequently, the incumbent’s marginal benefit of innovation is lower than that of the entrant and hence it will have less incentive to innovate than the entrant. An innovation is viewed as radical in the organizational sense if the innovation is competence-destroying with respect to a firm’s technical capabilities (Henderson 1993, Tushman and Anderson 1986). As a result of a competence-destroying innovation, the incumbent’s marginal cost for R&D investment is higher compared to the entrant equipped with the relevant technical capabilities. As a result, the incumbent will have less incentive to invest than an entrant with an appropriate capability set. Thus, while these two literatures take different perspectives, they share a common logic: incumbent firms fail because they under-invest in radical innovations. Further, such under-investment behavior can be justified on the basis of a rational calculation.

Contrary to these explanations, however, some in-depth case studies have shown that incumbent firms often failed despite their heavy investments in radical innovations (Rosenbloom 2000, Tripsas 1997, Tripsas and Gavetti 2000). Tripsas (1997) shows that a lack of investment in R&D was not responsible for incumbent failure in the typesetter industry that went through three generations of radical transformations. Incumbents actually invested large amounts in the new product generations: “qualitative data from interviews with both management and development engineers indicate that the level of investment by incumbents was at least equivalent to that of new entrants” (Tripsas 1997: 130). However, the technical performance of products developed by incumbents during each new technology period was inferior to the performance of the entrant’s products. Relatedly, Tripsas and Gavetti (2000) show that Polaroid committed substantial investments to digital imaging technologies when such technologies first

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1 Another reason we might see the incumbent be less efficient is due to the adverse productivity effects of size in innovative activities (e.g., Elfenbein, Hamilton and Zenger 2010, Williamson 1975, 1985, Zenger 1994).
emerged as a potential threat to its instant camera business: “An electronic imaging group was formed in 1981, and as part of this effort work began on a microelectronics laboratory. The microelectronics laboratory opened up in 1986 after a capital investment of about $30 million, and with an operating budget of about $10 million/year. By 1989, 42 percent of R&D dollars were devoted to exploring a broad range of digital imaging technologies (Tripsas and Gavetti 2000: 1152).” Despite such significant efforts, Polaroid declared bankruptcy in 2001. Rosenbloom (2000) shows that National Cash Register Company (NCR) was among the pioneers seeking to make a transition to electronics. NCR started engaging in in-house research activities in electronics as early as 1938 and entered the computer industry in 1953 by acquiring Computer Research Corporation (CRC), one of the first computer companies. While NCR eventually survived the technological change after decades of restructuring, it encountered a deep crisis in the early stages of this transition.

This gap between the theoretical literature and empirical observations is further illustrated by Kodak’s investment behavior vis-à-vis digital photography (Gavetti, Henderson and Giorgi 2004a, b). Digital photography appears to represent a radical innovation in both an economic and organizational sense. First, from an economic perspective, digital imaging can displace traditional film-based imaging. As Kodak entered the digital imaging field, it has to cannibalize its own traditional film sales. In contrast, the entrants from the computer and consumer electronics industries, such as HP and Sony, did not face the same problem. Thus, other things being equal, this cannibalization effect should have decreased Kodak’s incentive to invest in the digital imaging field.

Perhaps a more fundamental factor in determining Kodak’s investment behavior, however, is the shift away from the chemistry-based technology domain of silver-halide film to the electronic-based digital technology domain of digital cameras (Gavetti et al. 2004a, b). R&D initiatives along the new technology domain rendered obsolete the skills and knowledge that Kodak accumulated in the chemistry-based domain. In contrast, new entrants, including both new ventures and de alio entrants coming from electronic and computer industries, had a capability set consonant with the new technology domain. Thus, existing theories of both economic substitutes and competence-destroying change would predict that Kodak would lag behind in investing in digital photography.

However, in spite of these considerations, “Kodak had been investing heavily in digital imaging since the early 1980s, pioneering image-sensor technology in 1986 and entering the market with a variety of products during the 1990s” (Gavetti et al. 2004a: 1). By 1993, the company had already spent $5 billion, or 40% to 50% of its total R&D budget, on digital imaging R&D (Gavetti et al. 2004a, b). Despite these enormous efforts, Kodak has not achieved commercial and technical success in the digital camera market. While Kodak has been able to secure a significant share of the US digital camera market in unit
volume, Kodak lost $60 on every digital camera sold in 2001 and continued to post losses at least until 2003 (Gavetti et al. 2004a, b).

One explanation for the above paradox is agency behavior: Managers in incumbent firms, such as Kodak, squandered their retained earnings on new technologies in which they should not have invested since they did not have relevant capabilities for such new technologies. As a consequence, these incumbents spent an enormous amount of capital on such technologies but did not obtain an adequate return for their shareholders. From this perspective, such incumbent firms would have better served their shareholders by retuning cash via dividends or share buybacks (Jensen 1993). We do not disagree with this possibility. In this study, however, we ask the following question: Can an incumbent’s investment, such as Kodak’s multi-billion dollar investment in digital imaging, be understood to be economically rational or should it be viewed as a misuse of its capital? In broader terms, what is the economic rationale for incumbents’ substantial investments in radical innovations that in many instances may yield only modest success? We develop an economic model to address this question. The model is admittedly simple, as the main purpose is to provide a transparent analytical structure for us to conceptualize and integrate various issues around this topic in the technology strategy literature. The remainder of the paper is organized as follows. Section 2 outlines our perspective in resolving the above puzzle. Section 3 sets up the model structure, and Section 4 provides the analysis. Finally, section 5 offers some broader conclusions and implications.

2. A perspective on complementary assets and technical trajectories

Our explanation to the paradox characterized above centers around the impact of complementary assets on the incumbent firm’s investment behavior with respect to radical innovations. Teece’s (1986) work on the role of complementary capabilities brought to light the issue that the relevant capability set for firms is composed not only of technical capabilities, but also complementary capabilities in manufacturing and marketing. Subsequent to Teece (1986), Mitchell (1989) and Tripsas (1997) demonstrated the power of complementary capabilities in buffering established firms from the competitive forces wrought by changes in an industry’s technical basis. However, perhaps because the original purpose of defining complementary assets is to characterize the innovator’s ability to appropriate value from R&D investments conditional on a successful R&D outcome (Teece 1986), the previous literature on complementary assets has tended to focus on the effect of complementary assets on the ex-post performance of incumbent firms (Hill and Rothaermel 2003). We take this line of reasoning further and argue that complementary capabilities also importantly affect firms’ ex-ante level of R&D investment.
and its choice of technical trajectory. As characterized by Dosi (1982), a technological trajectory corresponds to a pattern of problem-solving and technical progress within a given technological paradigm. For our purposes, we use the term to connote the particular class of technologies the firm is building upon and the nature of the technological performance attributes it is striving to achieve.

In our analysis, we consider two forms of heterogeneity: heterogeneity with respect to technical trajectories and heterogeneity with respect to firms’ complementary capabilities. The prototypical setting one might imagine is an established firm with a substantial stock of complementary capabilities (ex., substantial downstream resources with regard to distribution and brand-name), but having its old technical basis negated by the emergence of new technologies and facing a decision as to which technical trajectory to invest in: its existing trajectory or the new trajectory suggested by this prospective technological change. In contrast, potential entrants may lack complementary capabilities, but have a high level of efficacy in making advances in the new technical domain. Our analysis recognizes that the link between investments, trajectory choices, and market outcomes is mediated by the presence of complementary assets. What is central to this perspective is the heterogeneity along different dimensions of the firm and the interdependence among them (Gulati and Puranam 2009, Helfat 1997, Lenox, Rockart and Lewin 2006, 2007, 2010, Mitchell 1989, Sosa 2009, Teece 1986, Tripsas 1997). Specifically, complementary assets can have the following dual role in affecting incumbents’ R&D investment.

On the one hand, complementary assets amplify returns on R&D investments for incumbent firms, thereby increasing incumbent firms’ economic incentive to invest in the new technical domain. Specifically, given the same R&D efforts, a larger stock of complementary assets allows a firm to appropriate a higher value (Teece 1986, Arora, Fosfuri and Gambardella 2001, Girotra, Terwiesch and Ulrich 2007). This implies a higher marginal benefit from R&D investment and thus a higher investment incentive. The empirical findings of Mitchell (1989) and King and Tucci (2002) that experience in prior sub-fields is positively associated with a firm’s likelihood of entering new, related sub-fields is consistent with this argument. Even more directly supportive of the above argument is Helfat’s (1997) work that indicates that firms are more likely to develop technologies that can utilize existing complementary technologies.

On the other hand, however, complementary assets may also bias incumbents’ choice of technical trajectories. Specifically, complementary assets can be trajectory specific in the sense that they are valuable in conjunction with a certain trajectory but lose significant value in conjunction with other ones. Therefore, incumbents endowed with complementary assets may have an incentive to choose a technical

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2 In related work, Dew, Goldfarb, and Sarasvathy (2006) examine the effect of complementary assets on investment incentives in the absence of a trajectory choice and thereby extend Reignanum’s (1983) analysis.
trajectory along which they can leverage their complementary assets, even if such a trajectory has a lower inherent promise to be preferred by the market.

Combining the above two perspectives, we provide a point of view in which complementary assets play a dual role in incumbents’ investment behavior toward radical innovations: Complementary assets are not only resources [pipes] that can buffer firms from technology change, but are also prisms through which they view those changes, in terms of both the magnitude of resources that should be invested and the trajectory to which these resources should be directed. When complementary assets are specific to a less promising technical trajectory, the incumbent is faced with a tradeoff between leveraging complementary assets and choosing a more promising technical trajectory.

To illustrate this tradeoff, reconsider the case of NCR noted earlier. After NCR acquired an early leader in the computer industry (CRC), NCR integrated CRC’s research activities in computer technology into the framework of NCR’s “overall product development program” in order to leverage NCR’s extensive sales forces, one type of complementary assets (Rosenbloom 2000: 1087). However, the choice of technical trajectory was also modified. “The binary arithmetic and limited input–output (I/O) capabilities of the 102-A [a general purpose computer] were well suited to scientific use, but appeared to the people in Dayton [where NCR’s headquarters is located] as obstacles to business application. As a senior engineer commented, ‘when you talked about a binary machine, you scared our salesmen’ (Rench 1984: 26)…. Under pressure from Dayton, CRC designed the 102-D, using decimal arithmetic...”

Similarly, while Polaroid invested a significant amount in digital photography very early on, their digital efforts were “guided by a desire to eventually develop an instant digital camera/printer product termed ‘PIF’ for Printer In the Field...As the 1984 Annual Report’s Letter to shareholders stated, ‘We believe that there is considerable potential in developing new hybrid imaging systems that combine instant photography and electronics.’...Since the output was to be on instant film, [the PIF concept] leveraged the firm’s strong film-manufacturing capabilities. It was also, however, consistent with the firmly held belief in a razor/blade model (Tripsas and Gavetti, 2000: 1152).” Kodak followed a similar razor/blade model. Indeed, much of Kodak’s early investments in digital photography derived from its attempt to leverage complementary assets in the film business such as distribution channels and photo finishers. Kodak also developed hybrid products, such as the Photo CD, that allow customers to both store and view digital images from CDs on computer, which they can then print at home or in store (Benner 2010, Gavetti et al. 2004a).

Across these examples, it is clear that, while the probability with which the technical trajectory chosen by the incumbents is to be preferred by the market may be lower than that for alternative technical

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3 We draw the pipe/prism analogy from Podolny (2001).
trajectories, this probability is not zero. Should this technical trajectory be preferred by the market, the incumbent is better able to fully leverage its existing complementary assets and gain greater market success. Therefore, for a given range of complementary assets, it may be optimal for the incumbent to choose the less promising technical trajectory. Moreover, these complementary assets may provide an incentive for the incumbent to invest more than the entrant *ex ante*. *Ex post*, however, should the technical trajectory that is chosen by the incumbent prove not to be an effective way to engage the market, either as a result of the possibility of technical progress along the performance dimensions pursued by the firm or the market’s valuation of those performance dimensions, the incumbent may have an inferior market outcome under certain conditions even with its higher investments. The incumbent firm is betting on the trajectory that yields, in expectation, the greatest profits; however, due to the impact of its existing stock of complementary capabilities, this is a different calculation than choosing the technical trajectory that is most likely to prove to be promising. As a consequence, it should not be uncommon to observe incumbent firms making what appear to be *ex-post* bad “bets”. We feel that the dual role of complementary assets can help explain situations like Kodak’s investment behavior and resulting market outcomes in digital photography. Kodak’s stock of relevant complementary assets in the imaging industry created strong economic incentives to invest in the new technical domain. However, in order to leverage its complementary assets, Kodak chose a technical trajectory that engages digital technology but in a manner that enables the firm to link this new technology to its existing assets and ways of competing (profiting from the development of images), despite possibly being aware that a more disruptive approach to digital photography might prevail.

Complementary capabilities are both an asset to be leveraged, but at the same bias a firm’s strategic choices. As a result of this dual effect, firms may rationally invest large sums in technology efforts that yield a relatively modest rate of technical advance. The incumbent may invest heavily but achieve a lower likelihood of technical leadership than similar investments yield for new enterprises established to pursue these new technological opportunities. It is thus important to recognize that the incumbent may choose different technical trajectories and therefore to distinguish between investment as an input or a behavior (dollars spent on R&D and acquiring new technologies) and the consequences or outcomes that stem from such investments (relative distance from the technology frontier, patented new technologies, successful products, and the like).

An important backdrop to these arguments is the question of the degree to which the market for complementary assets and technology are imperfect. To the degree that these markets do not function well, the entrant cannot get access to complementary assets (e.g., through contracting) and the incumbent may not gain access to external technology (e.g., through licensing). We assume that it takes time for the entrant to internally develop complementary capabilities since the adjustment costs of developing
complementary assets in a short period of time are prohibitive (Dierickx and Cool 1989). Furthermore, following Teece’s original work (Teece 1986), we assume that the market for complementary assets is imperfect, because such assets tend to be co-specialized or specialized to the firm and thus transaction costs are high. In the absence of these assumptions, the competitive supply of complementary assets would cause the asymmetry between the incumbent and the entrant to disappear or certainly dissipate. Similarly, we assume that the markets for technology are imperfect (Nelson 1959; Arrow 1962) and hence do not consider the transaction activities for technology between the incumbent and entrant, which simplifies our analysis in that the two firms’ payoff structure is determined purely by product market competition. The extent to which markets for technology are able to function depends on a number of factors, including the nature of knowledge and intellectual property rights and related institutions (Arora et al. 2001, Dushnitsky 2010, Dushnitsky and Lenox 2005, Dushnitsky and Shaver 2009, Elfenbein 2007, Goldfarb 2008, Ziedonis 2007). We discuss possible extensions in the discussion section.

In the next section, we formalize the above perspective with a simple model and in the following section characterize the basic patterns of behavior suggested by the model.

3. Model setup

We consider a stylized two-stage model to examine firms’ investment decisions with respect to a radical innovation. In the first stage, an incumbent firm, denoted by $I$, is aware of an emerging new technical trajectory and an entrant firm, denoted by $E$, who plans to enter the market by investing in R&D along the new trajectory. Firm $I$ can choose to invest either along the new trajectory or the old technical trajectory that can potentially better leverage its complementary asset. Let $r \in \{0,1\}$ represent firm $I$’s chosen trajectory, where 1 represents the new technical trajectory and 0 represents the old technical trajectory. To model firm $I$’s trajectory choice non-trivially, we assume the market’s preferred trajectory, denoted by $t \in \{0,1\}$, is uncertain, and let $p = \text{Prob}(t = 1) > 0.5$. In this stage, we assume firm $I$ plays as a Stackelberg leader who chooses its trajectory $r$ and its R&D investment level $u_I$ before firm $E$ chooses its R&D investment level $u_E$.

Firms’ technical trajectory, R&D investment, and the market’s preferred trajectory determine the “base utility” of firm $i$’s product, denoted by $U_i$. In particular, we assume the base utility for firm $E$’s product would make it sense that the entrant plans to enter the market by investing along the new trajectory. In fact, our results do not rely on this assumption.

To guarantee the existence of a unique equilibrium in a Stackelberg game, researchers usually assume that the follower would choose the action most favorable to the leader among the set of the follower’s optimal actions (see, for example, footnote 17 in Moorthy (1988)). Furthermore, we also examined the case where the entrant is the Stackelberg leader and our main results hold. We have also examined the model under a Nash equilibrium in which the firms move simultaneously. We can derive similar results under a Nash setting; however, there exists multiple Nash equilibria, including mixed strategy equilibria. Therefore, for simplicity we focus on the Stackelberg setting.
product is $U_E = \delta^{1-t}u_E$, $0 < \delta < 1$. Namely, while its base utility increases in its R&D investment, it is discounted by $\delta$ if there is a mismatch between its trajectory (i.e., the new trajectory) and the realized market-preferred trajectory. Similarly, if firm $I$ chooses the new trajectory, we assume that $U_I = \delta^{1-t}u_I$. However, if firm $I$ chooses the old trajectory, we assume that $U_I = \delta^t A^{1-t}u_I$, where $A > 1$ represents firm $I$’s complementary asset. Thus, the critical asymmetry between the incumbent and entrant is the incumbent’s possession of complementary asset along the old trajectory. Specifically, firm $I$ is assumed to have some complementary asset that may increase its product’s base utility but such complementary asset is trajectory-specific – it will be leveraged only when the incumbent chooses the old technical trajectory and when the market prefers the old trajectory. We make this assumption regarding the limited fungibility of complementary assets to highlight the central tradeoff faced by the incumbent. In the subsequent analysis of the robustness of the model in section 4.1, we allow complementary assets to have some degree of fungibility and retain some value in the new trajectory. Table 1 summarizes the two firms’ base utility functions under different scenarios.

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In the second stage, the two firms engage in quantity competition in the market. Let $q_i$ denote firm $i$’s product quantity. We consider a linear demand system where $p_i = U_i - \beta q_i - \gamma q_j$ with $\beta > \gamma > 0$ for $i \in \{I, E\}$ and $j \in \{I, E\}, j \neq i$. The above linear demand curve can be derived by considering a representative consumer with utility given by $U(q) = U_1 q_1 + U_2 q_2 - \frac{1}{2} (\beta q_1^2 + 2\gamma q_1 q_2 + \beta q_2^2)$ (Vives 2001: 145) and, as a result, the intercept $U_i$ in the linear demand curve can be interpreted as capturing the base utility of firm $i$’s product defined above. A similar demand relationship has also been used in Sutton (1997: 58-59) in modeling the impact of R&D investment on product quality.

**Market competition equilibrium in the second stage**

Given the firms’ technical trajectory and R&D investment level, we can specify their second-stage profit functions stemming from product market competition. We assume both firms have marginal production cost normalized to zero. Let $\Pi_i(U_i, U_E)$ denote the equilibrium profit of firm $i$ given $U_i$ and $U_E$. If $2\beta U_i - \gamma U_j > 0$ for both $i = I, E$, both firms choose positive production quantity, and the equilibrium

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6 One could also explore the effect of asymmetry in their technological capabilities with respect to the different trajectories. If so, a natural assumption here would be that the incumbent is less capable, perhaps as reflected in a lower marginal return to R&D investment than the entrant. Clearly, such a property would decrease the incumbent’s incentive to invest. We wish to explore a, in some sense, stronger case, where the incumbent has no intrinsic disadvantage with respect to the new technological trajectory but still, as a result of its complementary capabilities, faces a very different decision calculus than that of the entrant.
production quantities and profits are given by $q_l = \frac{1}{4\beta^2 - \gamma^2} (2\beta U_l - \gamma U_j)$ and $\Pi_l(U_l, U_E) = \beta q_l^2$. If $2\beta U_l - \gamma U_j > 0$ holds only for one firm, for example, $i = I$, then only firm $I$ produces and we have $q_l = \frac{1}{2\beta} U_l$, $q_E = 0$, $\Pi_l(U_l, U_E) = \beta q_l^2$, and $\Pi_E(U_l, U_E) = 0$. This is similarly true for $i = E$.

**R&D investment equilibrium and incumbent trajectory choice in the first stage**

Following the literature (Rosen 1991; Sutton 1997), we assume that the cost of achieving $u_i$, $C(u_i)$, is sufficiently convex such that all profit functions are quasi-concave. A sufficient condition is that $C(u_i)$ increases in $u_i$. Let $\Sigma_i^r(u_i, u_E)$ be firm $i$’s expected total profit given $u_i$ and $u_E$, if firm $I$ chooses trajectory $r$. Thus, we have

$$\Sigma_i^1(u_i, u_E) = p\Pi_i(u_i, u_E) + (1 - p)\Pi_i(\delta u_i, \delta u_E) - C(u_i)$$ (1)

$$\Sigma_i^0(u_i, u_E) = p\Pi_i(\delta u_i, u_E) + (1 - p)\Pi_i(Au_i, \delta u_E) - C(u_i)$$ (2)

Conditional on firm $I$’s trajectory choice $r$, firm $i$’s R&D investment in equilibrium, denoted by $u_i^r$, is given by $u_i^r = \arg \max_{u_i} \Sigma_i^r(u_i, u_E(u_i))$, where $u_E^r(u_i) = \arg \max_{u_E} \Sigma_E^r(u_i, u_E)$, and $u_E^r = u_E^r(u_i^r)$. Therefore, in equilibrium, firm $I$ chooses trajectory $r = 0$ over $r = 1$ if and only if $\Sigma_i^0(u_i^0, u_E^0) > \Sigma_i^1(u_i^1, u_E^1)$.

**4. Analysis**

We first characterize the effect of the incumbent’s complementary asset on the two firms’ investments and expected total profit in equilibrium.

**Lemma 1:** If firm $I$ chooses the new trajectory, in equilibrium the two firms’ investment and expected total profit do not depend on $A$. If firm $I$ chooses the old trajectory, in equilibrium firm $I$’s (firm E’s) investment and expected profit increases (decreases) as $A$ increases.

**Proof:** See Appendix.

Lemma 1 provides the key mechanisms regarding the economic incentives created by the incumbent’s complementary assets. When the incumbent chooses the old trajectory, its expected profit will increase with the level of its complementary assets, as long as the likelihood that the market prefers
the old trajectory, however small, is greater than zero. The reason is that the existence of complementary assets increases the incumbent’s marginal return of R&D investment and hence encourages the incumbent to invest more in equilibrium. In contrast, the incumbent will not be able to leverage its complementary assets if it chooses the new trajectory. Therefore, as the level of the incumbent’s complementary assets increases, the incumbent is more likely to choose the old trajectory. Lemma 1 also shows the negative impact of the incumbent’s complementary assets on the entrant. The entrant is discouraged to invest in the new innovation due to two effects. One is a direct effect, namely, the complementary asset increases the incumbent’s ability to appropriate from the innovation and hence reduces the entrant’s marginal revenue. The other is an indirect effect caused by the increase of the incumbent’s investment.

Lemma 1 provides a rationale for the incumbent’s heavy investment in radical innovations. Next we address the central question that we posed in the Introduction: Why incumbent firms often failed in the face of radical innovations despite their heavy investments. To this purpose, we further compare the market outcome of the incumbent’s R&D investment vis-à-vis the entrant. In characterizing the market outcome, we examine how the two firms’ trajectories differ, which firm invests more, and which firm leads the market in terms of achieving larger market share. It is important to note that the comparison in terms of ex-post market outcome may be different than the comparison in terms of ex-ante investment. Specifically, when the two firms choose the same technical trajectory, the investment amount and market outcome have a one-to-one relationship. However, when firms are likely to take different technical trajectories, such a relationship does not hold. With heterogeneous technical trajectories, an equal investment in R&D may not lead to an equal market outcome. The following proposition shows that the market outcome can be characterized by three threshold values of the incumbent’s complementary assets.

Proposition 1: For any $0 \leq \delta \leq 1$, there exists three thresholds $A^r(\delta) \leq A^u(\delta) \leq A^l(\delta)$ such that i) if $1 < A < A^r(\delta)$, firm I chooses the new trajectory $r=1$ (i.e., $\Sigma_i^0 < \Sigma_i^1$), ii) if $A^r(\delta) < A < A^u(\delta)$, firm I chooses the old trajectory $r=0$ (i.e., $\Sigma_i^0 > \Sigma_i^1$) and invest less than firm E, iii) if $A^u(\delta) < A < A^l(\delta)$, Firm I chooses the old trajectory $r=0$ (i.e., $\Sigma_i^0 > \Sigma_i^1$) and invests more than firm E, but does not lead the market (i.e., $\delta u_i < u_E$) if the market values the technical trajectory $t=1$, iv) if $A^l(\delta) < A$, firm I chooses the old trajectory $r=0$, invests more than firm E and leads the market (i.e., $\delta u_i > u_E$), even if the market values the technical trajectory $t=1$.

Proof: See Appendix.

Proposition 1 shows that firm I’s trajectory choice and investments depend on both the level of complementary assets and the penalty from technical mismatch. A higher level of complementary assets
encourages the incumbent to choose the old trajectory, and encourages large investment given its choice of the old trajectory. Further, when we look at the choice of technical trajectory and investment level simultaneously, various interesting possibilities emerge. Specifically, by varying the degree of heterogeneity with regard to the stock of complementary assets and the penalty from technical mismatch, Proposition 1 characterizes distinct regimes with respect to choices of technological trajectory and product market outcomes. Figure 1 illustrates these regimes for the case where $p=0.7$, $\beta=1$, and $\gamma=0.5$, where the vertical axis $A$ captures the incumbent’s higher complementary assets (recall the entrant’s complementary assets are normalized as one), while the horizontal axis $\delta$ captures the consequences of choosing different technical trajectories. In all numeric studies, we use the cost function $C(u_i) = (\max(u_i - 1,0))^2$.

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The dotted region in Figure 1 corresponds to a setting in which the incumbent chooses the new trajectory and competes on the same basis as the entrant. In many cases, the incumbent is not constrained by their existing complementary assets as they have a modest number of complementary assets and therefore they are not that consequential to the firm’s calculus as to how to approach the market. As a result, the incumbents are willing to give up their historical endowment and take on the new technical trajectory. The grey region corresponds to a setting in which the incumbent chooses the less promising technical trajectory, invests less than the entrant, and experiences a lower market share if the market prefers the new technical trajectory. This setting is consistent with the empirical observations made by Tushman and Anderson (1986) that incumbents tend to invest less in competence-destroying innovations where they lack competence. At the same time, however, this setting offers an alternative explanation to this empirical observation: the incumbent’s lower competence with respect to the new innovation may be an outcome of their endogenous choice of how the firm chooses to respond to the technological opportunities that they face.

The white region depicts a setting in which the incumbent chooses the old trajectory but still “wins” despite the fact that the market prefers the new trajectory. This setting represents a kind of “lock-in” region in which the market prefers the new technology but with not quite enough intensity ($\delta$) relative to the incumbent's old technology.

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7 This cost function is chosen solely for the ease of numeric study, as it satisfies the condition that $\frac{C'(u_i)}{u_i}$ increases in $u_i$ and it guarantees that the profit function is well behaved. Further, we can understand the 1 in this functional form as a normalization of the minimum investment required to enter, which does not cost anything but guarantees some minimum “base utility” of products. Numeric results are similar if we use different normalization values such as 0.5.
to the incumbent’s stock of complements (A).\(^8\) This finding is akin to work on standards (Arthur 1989, Shapiro and Varian 1999) in which it is shown that inferior technologies may come to dominate as a result of early market presence and the presence of strong network externalities.

If the incumbent has indeed amassed a sufficiently large stock of complementary assets, these complementary assets may create a sufficient incentive for the incumbent to invest significantly more than the entrant. In this case, even if the incumbent takes an inferior technical trajectory, the incumbent may still maintain a larger market share due to its large investment. Consider the engagement of newspaper firms in digital media as characterized by Kim (2010). Kim (2010) shows that firms such as the New York Times, which has a large set of complementary assets (e.g., content, journalist team, social status) are more inclined to develop websites that develop digital media in a manner similar to that of print media, while firms such as the Denver Post, lacking in such complementary assets, are more likely to develop websites that are more distinctive to the technology of digital media. Both the look and feel of the two websites and the degree of interactive components seems consistent with this argument. In contrast, a new entrant such as Slate or Yahoo adopted a pure digital form with little reference to traditional print news.

The black region in Figure 1 corresponds to the puzzle that we introduce in the beginning of the paper, where the incumbent chooses the old trajectory, invests more, but achieves a lower market share than the entrant if the market prefers the new trajectory. The prior examples of Kodak, Polaroid, and NCR all correspond to this regime. Thus, we are suggesting that these firms, despite their unfavorable outcomes, may well have made rational investments that attempted to engage emerging technologies in ways that allowed them to leverage their existing complementary assets. Indeed, as Benner (2010) shows, stock analysts reacted quite favorably when Kodak invested in “hybrid” products.

Proposition 1 lays out the overall distribution of various possible regions; however, it does not yet specify the conditions under which each region will occur. In particular, it does not specify the conditions under which the black region, which is of central interest to this study, will exist. In the following proposition, we specify such conditions.

Proposition 2: For any \(0 \leq \delta < 1\), there exists \(0 < \bar{\delta}(\delta) < 1\) such that \(A^*(\delta) > 1\) when \(p > \bar{p}(\delta)\).

There exists \(\delta > 0\) such that for all \(\delta < \bar{\delta}\), \(A^*(\delta) < A^!(\delta)\).

Proof: See Appendix.

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\(^8\) In the figures, due to the choice of parameter values, the black region hits the ceiling of the figures when the penalty from technical mismatch \(\delta\) is very small. In fact, the white region will exist even as the penalty from technical mismatch \(\delta\) goes to zero.
Proposition 2 states that the incumbent can choose between the old and the new trajectory when the likelihood of the new trajectory being preferred by the market is sufficiently large. Otherwise, it may be possible that the incumbent always chooses the old trajectory even when its complementary assets is the same as the entrant. More importantly, Proposition 2 states that there is a region in which the incumbent chooses the old trajectory and attains a smaller market share when the new trajectory is preferred by the market if \( p \) is large enough and \( \delta \) is small enough. This observation has the non-intuitive property that firm \( I \) rationally chooses to lose the market competition with a high probability.

The regime characterized by Proposition 1 and Proposition 2 helps explain why an incumbent can fail in the face of radical innovations despite its heavy investment. In our model, radical innovation is captured by the fact that, due to the emergence of a new technical trajectory, the entrant is not in a disadvantageous position vis-à-vis the incumbent in terms of technical capabilities; in that regard, the entrant can compete on the same basis as the incumbent. Furthermore, the incumbent has to choose between the old and the new technical trajectory in pursuing the radical innovation. Should the incumbent choose the old trajectory, it has an incentive to invest more than the entrant due to the existence of complementary assets, which can amplify the return from a given level of investment. At the same time, however, the existence of complementary assets also makes it more attractive for the incumbent to choose the old trajectory, as it can fully leverage complementary assets when the market values the old trajectory. When the parameters are in the black region of Figure 1, the above two forces generate this distinct regime.

Propositions 1 and 2 characterizes a kind of path dependency, but it differs from the standard notion of path dependency, which generally suggests some behavioral mechanism that reinforces the firm’s current pattern of action and investment. In our model, the incumbent is acting rationally and is forward looking. It is induced by its complementary assets to make its particular technical choice. The incumbent has the option to give up its complementary assets and take the new trajectory, but it is a rational decision for them not to do so. It is true that the new technical trajectory is more likely to be preferred by the market, but this is not certain. Therefore, a little bit of uncertainty and the inducement of complementary assets can generate the pattern that, \textit{ex post}, the incumbent seems to make a mistake. It invests heavily in its existing trajectory despite evidence to suggest that the new, alternative trajectory is more likely to be preferred by the market. Such behavior may appear to be irrational and perhaps reflect some pathology of organizational inertia. But, \textit{ex ante}, despite the likelihood that the new trajectory may be preferred, it still may be rational for the incumbent not to, effectively, throw away their complementary assets and become equivalent to the entrant. It is certainly possible that a firm may irrationally ignore the possible benefits of leveraging new technologies, but it is important to recognize...
that incumbents, in the face of radical innovations, may be sensibly maximizing their *ex-ante* expected returns and not failing to realize the full strategic implications of their decisions.

We next examine the impact of complementary assets on market outcomes when the market prefers the new trajectory. This analysis offers testable implications and highlights the mechanisms that lead to such implications. Specifically, we use market share to measure the product market outcome.

*Proposition 3:* There exists $0 < \delta < 1$ such that when $0 < \delta < \delta_p$, and the new trajectory is preferred by the market, firm I’s market share is non-monotonic as $A$ increases from 1 to arbitrarily high levels. In particular, firm I’s market share is a constant with respect to its level of complementary assets when $A < A'(\delta)$, drops below the constant when $A$ exceeds $A'(\delta)$, increases as $A > A'(\delta)$ increases, and exceeds firm E’s market share when $A > A'\delta$.

Proof: See Appendix.

Proposition 3 states that we can observe a non-monotonic relationship between complementary asset and firm I’s market share for a given level of $\delta$ when the new trajectory is preferred by the market. This result has two conceptual drivers. One is a switch in "regime" (choice of old or new trajectory) and the other is the marginal impact of changes in complementary assets on performance within the same regime. As a result, an increase in $A$ may lead to a jump shift downward in performance with the change in regime and then further increases lead to incremental increases in market outcomes within a given “regime”. Specifically, when the level of complementary assets is low, it is not worthwhile for the incumbent to choose the old trajectory. Therefore, the incumbent chooses the new trajectory and in some sense becomes equivalent to the entrant. As the level of complementary assets increases to an intermediate level, however, the incumbent switches to the old trajectory. Now, when the new trajectory is preferred, clearly the incumbent will be penalized, *ex post*, should the market prefer the new trajectory. However, note that such penalty is compensated for the possibility, albeit perhaps small, that the old trajectory may be preferred. When the level of complementary assets is sufficiently high, the incumbent will do well even if the new trajectory is realized. This strong performance is not the result of the firm being buffered by complementary assets. Rather, the firm’s complementary assets induce the firm to invest in high levels of R&D, resulting in the superior performance. We illustrate this case with a numerical example in Figure 2 ($\delta = .8$, $p=.7$, $\beta=1$, $\gamma=.5$). As we can see, the incumbent’s market share takes a U-shape with the level of complementary assets when the new trajectory is preferred by the market. This is mostly driven by a sharp drop in sales around $A=1.2$ (the point at which the incumbent shifts from the old to the new trajectory).
In the following analysis, we examine the shape of the three thresholds identified in Figure 1. Both the equal-market share curve $A^I(\delta)$ (the lower boundary of the white region) and the equal-investment curve $A^u(\delta)$ (the lower boundary of the black region) increase almost monotonically in Figure 1, because a larger penalty associated with the choice of the less preferred technological trajectory requires a higher level of complementary assets to compensate and generate equal investment incentives and market outcome. However, both the equal-trajectory (the upper bound of the dotted region) and the equal-investment lines (the lower bound of the black region) are flat when delta is small enough. This is because when $\delta$ is small, the incumbent does not produce when the market favors the new trajectory due to the fact that $2\beta u_I - \gamma u_E = 2\beta \delta u_I - \gamma u_E < 0$. As a result, both firms’ investments do not change with $\delta$ as $\delta$ goes to zero.

The equal-trajectory threshold $A^I(\delta)$ (the upper bound of the dotted region) exhibits an inverse-U shape as the penalty from technical mismatch $\delta$ changes from 1 to 0. This implies that for a lower level of complementary assets $A$, it is less profitable for the incumbent to choose the new trajectory when $\delta$ is either close to 1 or to 0, but more profitable to do so when $\delta$ has a moderate value. While the old trajectory is obviously attractive to the incumbent when it can leverage its complementary asset with low mis-match penalty ($\delta$ is close to 1), the old trajectory is also attractive to the incumbent when mis-match penalty is high ($\delta$ is close to 0) because the old trajectory better differentiates the incumbent from the entrant and hence would help it dominate the market should the market turn out to favor it.

To illustrate the above intuition, Figure 3a plots the incumbent’s expected profit depending on its trajectory choice. As it shows, while the incumbent’s expected profit decreases as $\delta$ decreases from 1 to 0 if the firm chooses the new trajectory, it is more L-shape in $\delta$ if the firm chooses the old trajectory. To help clarify why the incumbent’s expected profit weakly increases as $\delta$ is close to and approaches 0, Figure 3b plots the base utility $U_I$ of the two firms’ products given the market’s trajectory preference, assuming the incumbent chooses the old trajectory. As we can see, when $\delta$ is close to 0, the incumbent can only profit when the market prefers the old trajectory because in the other case when the market prefers the new trajectory, the incumbent’s product base utility is far dominated by the entrant’s. When the market prefers the old trajectory, the incumbent maintains a high level of product base utility as opposed to the diminishment of the entrant’s. This contrast leads to diminishing competition pressure when $\delta$ is close to and approaches 0 as the incumbent differentiates itself from the entrant by choosing the old trajectory.

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9 The equal-market share curve $A^I(\delta)$ increases monotonically. However, there is a slight drop between the upward increasing part and the flat part of the equal-investment curve $A^u(\delta)$. This drop is caused by the exit of the incumbent’s product when the market favors the new trajectory, because at this $\delta$ value $2\beta u_I - \gamma u_E = 2\beta \delta u_I - \gamma u_E = 0$. Foreseeing this, the entrant reduces its investment ex ante. Correspondingly, it is easier for the incumbent to invest more than the entrant; that is, the equal investment curve $A^u(\delta)$ drops.
4.1: Robustness to fungible complementary assets

In the above analysis, we assumed that the incumbent is able to leverage its complementary assets only when it chooses the old trajectory and the old trajectory is also preferred by the market (second to the last column of Table 1). We made this assumption in order to focus on the central mechanism at work in determining firms’ choices and their market outcomes. In this section, we relax this assumption by allowing for a certain degree of fungibility of complementary assets in the new trajectory. The last column of Table 1 presents a general form of the fungibility of complementary assets. If the incumbent chooses the old trajectory \( r = 0 \) but the market values the new trajectory \( t = 1 \), then the incumbent can still leverage its complementary assets but suffers from a discount; that is, the incumbent’s effective complementary assets becomes \( A^{\kappa_1} \), where \( 0 \leq \kappa_1 \leq 1 \). Similarly, if the incumbent chooses the new trajectory \( r = 1 \), the incumbent can also leverage its complementary assets to a certain degree; that is, the incumbent’s effective complementary assets becomes \( A^{\kappa_2} \), \( 0 \leq \kappa_2 \leq 1 \), whether the market values the old or the new trajectory. We can interpret \( \kappa_1 \) and \( \kappa_2 \) as the degree to which complementary assets are trajectory specific. When complementary assets are fully trajectory specific to the old trajectory, then \( \kappa_1 = \kappa_2 = 0 \); that is, the incumbent’s advantage in terms of complementary assets will disappear if the firm chooses the new trajectory, or when the incumbent chooses the old trajectory but the market values the new trajectory. In contrast, when complementary assets are fully trajectory independent, then \( \kappa_1 = \kappa_2 = 1 \), and the incumbent’s advantage in terms of complementary assets will fully retain whether it chooses the new or old trajectory and whether the market values the old or new trajectory.

Our results are in general robust to this more general setup, and in particular the distinct regimes we identified in Proposition 2. As \( \delta \) goes to zero, so does the base utility of the incumbent's product if it chooses the old trajectory and the market prefers the new trajectory. Therefore, the black region still exists in this setting as well. This region characterizes the case when the complementary asset is sufficiently large that the incumbent prefers the old trajectory but the value of delta is sufficiently small that the incumbent's effective investment diminishes once the market turns against the incumbent’s choice. The existence of the black region persists when \( \kappa_1, \kappa_2 > 0 \), because \( \kappa_1 \) and \( \kappa_2 \) only influence the incumbent's preference between the two trajectories, and determines how large a value of complementary asset \( A \) is required to be to turn the incumbent's preference toward the old trajectory.

However, since \( \kappa_1 \) and \( \kappa_2 \), the factors that affect the degree to which complementary assets are specific to a given technical trajectory, can influence the incumbent’s trajectory choice, the shape of the regions in Figure 1 is affected when we allow for a certain degree of fungibility of complementary assets.

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10 We could further introduce a \( \kappa_3 \) to separately represent the case when the market values the old trajectory and the case when the market values the new trajectory, but the mechanisms that we show below do not change.
A larger value of $\kappa_1$ makes the old trajectory more preferable, and hence it leads to higher investment and profit of the incumbent but lower investment and profit of the entrant if the incumbent chooses the old trajectory. Therefore, as $\kappa_1$ increases, the region (in the $A-\delta$ plane) where the incumbent prefers the old trajectory (the dotted region) shrinks, and the thresholds of equal-investment (the lower boundary of the black region) and equal-market-share (the lower boundary of the white region) decrease. The four figures of Figure 4a show this pattern.

A larger $\kappa_2$ makes the new trajectory more preferable and hence it leads to higher investment and profit for the incumbent but lower investment and profit for the entrant if the incumbent chooses the new trajectory. In contrast to its impact on trajectory choice, $\kappa_2$ does not affect the equal-investment and equal-market share thresholds because these two thresholds only concern what happens should the old trajectory be chosen, and if the old trajectory is chosen the value of $\kappa_2$ does not affect the outcome (i.e., the two firms’ investment decisions). Therefore, as $\kappa_2$ increases, the dotted region will expand and may ultimately swallow part or all of the grey region. The four figures of Figure 4b show this pattern.

5. CONCLUSION AND DISCUSSION

Complementary assets do not just shield firms from radical technical changes, but also affect investment incentives. While the existing literature has made the important point that complementary assets can, ex-post, influence product market and financial outcomes, the potential effect of complementary assets on economic incentives for ex-ante investment behavior has been under explored.

In comparing the behavior of incumbent and entrant firms, we highlight an important distinction between investment intensity and final outcomes. If firms’ R&D capabilities are homogeneous, it would be sufficient to examine only the magnitude of firms’ investment in new technologies, as homogeneous R&D capabilities imply that equal amounts of R&D investment lead to equal likelihoods of success. However, such an implication will not hold when firms’ technical capabilities are heterogeneous and in particular when they can make different choices of their technical trajectories. As a result, strategy research on radical innovations should distinguish between the magnitude of firms’ investments and the likelihood of technical success.

In conjunction, the above two observations can help explain the empirical puzzle that incumbent firms often fail in radical innovations despite their substantial R&D investments. In the face of radical innovations, the existing literature suggests that the incumbent will tend to invest less than the entrant. The dominant explanation of this within the economics literature is that the concern with cannibalization reduces the incumbent’s marginal benefit from innovative activities. The explanation popular in the strategy field is that the radical innovation reduces the incumbent’s relevant technical capabilities. However, in fact, we often observe incumbent firms aggressively investing in radical innovations. At the
same time, in spite of such investments, it is also not uncommon to observe that the incumbent is overtaken by the entrant in terms of technological leadership. However, these investments need not be irrational. The distinct regimes we identify in the analysis provide important insights into this phenomenon. The presence of complementary assets can enhance the incumbent’s ability to appropriate the gains from innovation and in turn create incentives to invest. At the same time, complementary assets induce the incumbent to choose a technical trajectory that can leverage its complementary assets but may be inherently less promising. Thus, complementary assets create a form of path dependency even if firms are making rational forward looking decisions regarding their investments. Further, our results suggest that incumbent’s low technological outcomes may be a consequence of its endogenous choice of technical trajectories, and not a consequence of exogenous change of the incumbent’s technical capabilities endowed from the past.

The distinct regimes identified in this study can generate non-linear relationships between technical success and the level of complementary assets. Firms with low level of complementary assets may give up such assets and pursue the new technological trajectory and in that respect become equivalent to the new entrant. It is also possible that firms with sufficiently high levels of complementary assets can still dominate the market, even with the choice of a seemingly less promising technological trajectory. However, in a broad range of settings, established firms, with their investment decisions influenced by their existing stock of complementary assets, may choose less promising technological trajectories and suffer adverse product market outcomes as a consequence. It is also important to recognize that complementary assets may be trajectory specific. If complementary assets are trajectory-specific, it makes sense for an incumbent firm to invest, but not in the same qualitative manner as a new firm. In contrast, if they are independent of trajectory, then the established firm should aggressively pursue the new trajectory. Finally, if the complements are rendered obsolete, the established firm has no basis of competitive advantage relative to the entrant.

Of course, there are a number of limitations to our analysis. First, the dynamic nature of the setting could be enriched. We do not consider differential entry timing of the incumbent versus the entrant. For instance, having some complementary assets, the incumbent could just let the new entrant enter first and wait until the uncertainty regarding the new technology resolves itself (Conner 1988, Mitchell 1989). The current study also assumes that both complementary assets and R&D capabilities are fixed and therefore treats them as exogenous parameters. It is certainly the case that these two factors evolve over time. One could extend the research by examining firms’ investments not only in R&D, but also with respect to investments in complementary assets. The investments along these two dimensions may be made simultaneously or sequentially. Further, firms’ R&D capabilities may change as a result of prior R&D investments.
Second, as discussed in the model setup, a critical assumption is that the market for complementary assets and technical capabilities are imperfect and, as such, an entrant cannot gain access to complementary assets (e.g., through contracting), while the incumbent may not gain access to external technology (e.g., through licensing). Relaxing this working assumption can lead to a fruitful research avenue that examines the role of licensing or mergers & acquisition activities between the incumbent and the entrant (Gans, Hsu and Stern 2002, Gans and Stern 2000). Building on the logic of Gans and Stern (2000), in the presence of licensing, alliances, and mergers & acquisitions, complementary assets can increase the incumbent's bargaining power in the licensing process and thereby lower the licensing fee paid to the entrant. The effects of complementary assets on the licensing fees that might be earned by an entrant, in turn, amplify the incumbent’s pre-innovation incentives, as well as its post-innovation returns. Thus, a large stock of complementary assets would still favor the incumbent by enhancing its returns on R&D relative to the entrant. This is ultimately the critical factor underlying our results regarding the rationality of the incumbent’s R&D investments in the face of radical technical change. Furthermore, the choice of technical trajectory in a given domain may impact the cost and effectiveness with which a firm can access and acquire these capabilities in the form of licensing, alliances, and acquisitions (Cohen and Levinthal 1990).

While these are important possible extensions, the current effort provides an important enrichment of our current treatment of the effect of complementary capabilities. Complimentary capabilities are not merely asset stocks that buffer firms from competitive dynamics. Complementary capabilities provide a critical component of the investment context for firms’ R&D decisions. Complementary capabilities can be leveraged to amplify the returns to an existing competitive position, but that act of leverage is not neutral with respect to the direction of the firm’s technical efforts. We highlight some of the tensions between the incentive to leverage and the need to make technologically appropriate choices and suggest how the balance of this tension may help to explain some of the empirical patterns and puzzles that we observe.
<table>
<thead>
<tr>
<th>Incumbent’s choice ( r ) ( r_i \in {0,1} )</th>
<th>Realized market preference ( t \in {0,1} )</th>
<th>Comments</th>
<th>Entrant’s product quality ( U_e )</th>
<th>Incumbent’s product quality ( U_i )</th>
<th>Generalization with fungible complementary assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r=0 )</td>
<td>( t=0 )</td>
<td>The incumbent chooses the old trajectory and the old trajectory is preferred by market. The incumbent can fully leverage complementary assets ( A ), and its R&amp;D effort is fully effective. However, the entrant suffers discount ( \delta ) in its R&amp;D effort due to the mis-match of trajectories.</td>
<td>( U_e = \delta u_e )</td>
<td>( U_i = Au_i )</td>
<td>( U_i = Au_i )</td>
</tr>
<tr>
<td>( r=0 )</td>
<td>( t=1 )</td>
<td>The incumbent chooses the old trajectory, but the market prefers the new trajectory. Therefore, the incumbent cannot leverage its complementary assets and suffers discount ( \delta ) in its R&amp;D effort due to mis-match of trajectories. The entrant’s R&amp;D effort is fully effective.</td>
<td>( U_e = u_e )</td>
<td>( U_i = \delta u_i )</td>
<td>( U_i = \delta A^{x_i}u_i )</td>
</tr>
<tr>
<td>( r=1 )</td>
<td>( t=0 )</td>
<td>The incumbent chooses the new trajectory, but the market prefers the old trajectory. The incumbent cannot leverage its complementary assets ( A ). Both incumbent and entrant suffer discount ( \delta ) in their R&amp;D effort due to mis-match of trajectory.</td>
<td>( U_e = \delta u_e )</td>
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<td>( r=1 )</td>
<td>( t=1 )</td>
<td>Incumbent chooses the new trajectory, and the market prefers the new trajectory. Therefore, the incumbent cannot leverage its complementary assets ( A ). The R&amp;D effort for both incumbent and entrant are fully effective.</td>
<td>( U_e = u_e )</td>
<td>( U_i = u_i )</td>
<td>( U_i = A^{x_i}u_i )</td>
</tr>
</tbody>
</table>
**Figure 1 Illustration of Proposition 1:** \( p = 0.7, \beta = 1, \gamma = 0.5 \). This figure is conditional on the case where the new trajectory is preferred by the market:

1. The white region is where the incumbent chooses the old trajectory but nonetheless invests more than the entrant and leads in market share.
2. The black region where the incumbent chooses the old trajectory, investment more than the entrant, but has less market share. It is also the region highlighted by Proposition 2.
3. The grey region is where incumbent chooses the old trajectory but invests less.
4. The dotted region is where the incumbent chooses the new trajectory.

\[ \rho=0.7, \beta=1, \gamma=0.5, \kappa_1=0, \kappa_2=0 \]

**Figure 2: Illustration for Proposition 3.**
Figure 3: Profits under Alternative Trajectory Choices

Figure 3a
\[ A=1.25, \phi=0.7, \psi=1, \gamma=0.5 \]

Figure 3b
\[ A=1.25, \phi=0.7, \psi=1, \gamma=0.5 \]

Figure 4: Robustness to more fungible complementary asset
a) Change in the shape of regimes as \( \kappa_1 \) varies.
b) **Change in the shape of regimes as $\kappa_2$ varies.**

- $\rho=0.7$, $\beta=1$, $\gamma=0.5$, $\kappa_1=0.4$, $\kappa_2=0.1$
- $\rho=0.7$, $\beta=1$, $\gamma=0.5$, $\kappa_1=0.4$, $\kappa_2=0.2$
- $\rho=0.7$, $\beta=1$, $\gamma=0.5$, $\kappa_1=0.4$, $\kappa_2=0.3$
- $\rho=0.7$, $\beta=1$, $\gamma=0.5$, $\kappa_1=0.4$, $\kappa_2=0.4$
REFERENCES


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Appendix: Proof for the propositions

Let $D_i(u_t, u_E) \equiv \frac{\partial n_i(u_t, u_E)}{\partial u_i}$ and $D_c(u_i) \equiv \frac{\partial c(u_i)}{\partial u_i}$. It is straightforward to show that $D_i(u_t, u_E)$ and $D_i(\delta u_t, \delta u_E)$ decrease in $u_E$, while $D_E(u_t, u_E)$ and $D_E(\delta u_t, \delta u_E)$ decrease in $u_t$. This implies that $u^*_E(u_i)$ decreases in $u_i$, because by assumption $C(u_E)$ is sufficiently convex such that the profit functions are quasi-concave, i.e., $pD_E(u_t, u_E) + (1 - p)D_E(\delta u_t, \delta u_E) - D_c(u_E)$ crosses zero only once.

Lemma 1: If firm I chooses the new trajectory, in equilibrium the two firms’ investment and expected total profit do not depend on $A$. If firm I chooses the old trajectory, in equilibrium firm I’s (firm E’s) investment and expected profit increases (decreases) as $A$ increases.

Proof: If firm I chooses the new trajectory, complementary asset $A$ does not enter firms’ profit functions (per Equation 1) and hence the equilibrium outcome does not depend on $A$.

If firm I chooses the old trajectory, first, we show that firm I’s (firm E’s) investment increases (decreases) as $A$ increases. First, notice that the left hand side of the firm E’s first order condition equation $pD_E(\delta u_t, \delta u_E) + (1 - p)D_E(Au_t, \delta u_E) = D_c(u_E)$ decreases. This implies that firm E’s best response $u^*_E(u_i)$ decreases in $A$. Second, we examine the first order condition for firm I’s problem, $pD_I(\delta u_t, u^*_E(u_i)) + (1 - p)D_I(Au_t, \delta u^*_E(u_i)) = D_c(u_t)$. Note that as $A$ increases $pD_I(\delta u_t, u^*_E(u_i))$ increases because $u^*_E(u_i)$ decreases, and as $A$ increases $(1 - p)D_I(Au_t, \delta u^*_E(u_i))$ increases because $D_I(Au_t, \delta u_E)$ increases in $A$ and decreases in $\delta u_E$. Therefore, we conclude that $u^*_I$ increases and $u^*_E$ decreases as $A$ increases. Last, we show that if firm I chooses the old trajectory firm I’s (firm E’s) profit increases (decreases) as $A$ increases. This is because $\frac{\partial \Sigma^0_I}{\partial A} = \frac{\partial \Sigma^0_I}{\partial A} + \frac{\partial \Sigma^0_I}{\partial u_t} \frac{\partial u_t}{\partial A} + \frac{\partial \Sigma^0_I}{\partial u_E} \frac{\partial u_E}{\partial A} > 0$ (since $\frac{\partial \Sigma^0_I}{\delta u_t} > 0$, $\frac{\partial \Sigma^0_I}{\delta u_E} < 0$, and $\frac{\partial u_t}{\partial A} < 0$) and $\frac{\partial \Sigma^0_E}{\partial A} = \frac{\partial \Sigma^0_E}{\partial A} + \frac{\partial \Sigma^0_E}{\partial u_t} \frac{\partial u_t}{\partial A} + \frac{\partial \Sigma^0_E}{\partial u_E} \frac{\partial u_E}{\partial A} < 0$ (since $\frac{\partial \Sigma^0_E}{\delta u_t} < 0$, $\frac{\partial \Sigma^0_E}{\delta u_E} < 0$, $\frac{\partial u_t}{\partial A} > 0$, and $\frac{\partial \Sigma^0_E}{\partial u_E} = 0$).

Lemma 2: If firm I chooses the old trajectory, in equilibrium firm I’s investment and expected profit increases arbitrarily large as $A$ increases arbitrarily large.

Proof: Since the term $(1 - p)D_I(Au_t, \delta u^*_E(u_i))$ in the left hand side of firm I’s the first order condition equation goes to infinity as $A$ goes to infinity, we have $u_t$ goes to infinity as $A$ goes to infinity. Since $\frac{\partial \Sigma^0_I}{\partial A} = \frac{\partial \Sigma^0_I}{\partial A} + (1 - p)u_t D_I(Au_t, \delta u_E) + D_I(Au_t, \delta u_E) = \frac{Au_t}{2p}$ when $Au_t \gg \delta u_E$, we have $\Sigma^0_I$ increases and goes to infinity as $A$ increases and goes to infinity.
Proposition 1: For any $0 \leq \delta \leq 1$, there exists three thresholds $A^r(\delta) \leq A^u(\delta) \leq A^l(\delta)$ such that i) if $1 < A < A^r(\delta)$, firm I chooses the new trajectory $r=1$, ii) if $A^r(\delta) < A < A^u(\delta)$, firm I chooses the old trajectory $r=0$ and invest less than firm E, iii) if $A^u(\delta) < A < A^l(\delta)$, firm I chooses the old trajectory $r=0$ and invest more than firm E but does not lead the market (i.e., $\delta u_I < u_E$) if the market values the technical trajectory $t=1$ (i.e., $\tilde{\Sigma}^0 > \tilde{\Sigma}^1$), iv) and if $A^l(\delta) < A$, firm I chooses the old trajectory $r=0$, invest more than firm E and leads the market (i.e., $\delta u_I > u_E$).

Proof: The existence of $A^r(\delta)$ is due to the fact that firm I’s expected profit increases and goes to infinity as $A$ increases and goes to infinity if firm I chooses the old trajectory, while its expected profit do not depend on $A$ if firm I chooses the new trajectory. The existence of $A^u(\delta)$ and $A^l(\delta)$ is due to the existence of $A^r(\delta)$ (i.e., firm I invests more than firm E when $A$ is small) as well as the fact that firm I’s investment amount increases and goes to infinity as $A$ increases and goes to infinity if firm I chooses the old trajectory. The ordering $A^r(\delta) \leq A^u(\delta)$ is due to the fact that firm I chooses the new trajectory and invests more than firm E when $A < A^r(\delta)$. The ordering $A^u(\delta) \leq A^l(\delta)$ is due to the definitions of these two thresholds and the fact that firm I’s investment monotonically increases as $A$ increases if firm I chooses the old trajectory. ■

Lemma 3: Suppose firm I chooses the old trajectory. For any $A>0$, there exists $\delta_I(A) > 0$ such that for all $\delta < \delta_I(A)$, $\delta u_I < u_E$ in equilibrium.

Proof: The lemma is true because as $\delta$ goes to zero, the firms’ equilibrium investments $u_I$ and $u_E$ are given by $\frac{(1-p)D_I(A u_I, 0) = D_c(u_I)}{pD_E(0, u_E) = D_c(u_E)}$, and are both positive. Thus, we have $\delta u_I < u_E$ for all $\delta$ small enough. ■

Proposition 2: For any $0 \leq \delta < 1$, there exists $0 < \bar{\delta}(\delta) < 1$ such that $A^r(\delta) > 1$ when $p > \bar{\rho}(\delta)$. There exists $\delta > 0$ such that for all $\delta < \delta$, $A^r(\delta) < A^l(\delta)$.

Proof: Let $(u^r_I, u^r_E)$ denote the equilibrium investment when firm I chooses trajectory $r$. For any $0 \leq \delta < 1$, there exists $0 < \bar{\rho}(\delta) < 1$ such that $A^r(\delta) > 1$ when $p > \bar{\rho}(\delta)$, because when $p$ equals 1 it is straightforward to show that $u^0_I < u^1_I$, $u^0_E > u^1_E$, and $\Sigma^1 = \Pi_1(u^1_I, u^1_E) - C(u^1_I) > \Sigma^0 = \Pi_1(\delta u^0_I, u^0_E) - C(u^0_I)$. There exists such a threshold $\delta > 0$ by Lemma 3. ■

Proposition 3: There exists $0 < \bar{\delta} < 1$ such that when $0 < \delta < \bar{\delta}$, $p > \bar{\rho}(\delta)$, and the new trajectory being preferred by the market, firm I’s market share is non-monotonic as $A$ increases from 1 to arbitrarily high levels. In particular, firm I’s market share is a constant with respect to its level of
complementary assets when $A < A^r(\delta)$, drops below the constant when $A$ exceeds $A^r(\delta)$, increases as $A > A^r(\delta)$ increases, and exceeds 50% when $A > A^l(\delta)$.

Proof: Proposition 2 implies that when $\delta < \bar{\delta}$ firm I’s market share increases as $A > A^r(\delta)$ increases and exceeds 50% when $A > A^l(\delta)$. When $A < A^r(\delta)$, the incumbent chooses the new trajectory, and its market share is a constant as $A < A^r(\delta)$ increases because the firms’ equilibrium investment do not depend on $A$. Denote the market share by $\mathcal{R}_u$.

As $\delta$ goes to zero, $\delta \mu^*_i / \mu^*_R$ goes to zeros when $A$ approaches $A^r(\delta)$ from above; namely, there exists a threshold $\tilde{\delta}$ such that for all $\delta < \tilde{\delta}$ we have $\delta \mu^*_i / \mu^*_R < R_u$ when $A$ approaches $A^r(\delta)$ from above. Let $\delta = \min \{ \delta, \bar{\delta} \}$. Therefore, when $0 < \delta < \tilde{\delta}$ and $p > \bar{p}(\delta)$, we have $1 < A^r(\delta) < A^l(\delta)$ and firm I’s market share is a constant when $A < A^r(\delta)$, drops below the constant when $A$ exceeds $A^r(\delta)$, increases as $A > A^r(\delta)$ increases, and exceeds 50% when $A > A^l(\delta)$. ■